

# **HGQ-09 Fabrication Report**

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## 1.0 Introduction

The two previous model magnets (HGQ07 and HGQ08) were manufactured with preload at the low and high end of the acceptable “window”, respectively. HGQ09 had a preload target halfway between that of HGQ07 and HGQ08 (the middle of the preload range). Annealing and stabrite coating of the strands, which was done on HGQ08, was eliminated. The coil curing cycle was revised for HGQ09 to control interstrand resistance, introducing a two-step cycle with low pressure/high temperature followed by a high pressure/low temperature step. HGQ09 includes a special bus assembly, identical to that used in HGQ08, except the stabilizer consisted of copper-only cable instead of superconducting cable. Strip heaters were manufactured by CERN, double element, with one transposition pitch of bare stainless steel alternating with one transposition pitch of copper coated stainless. The welded pack length was changed from 75mm to 38mm, allowing for more radial cooling passages within the collared coil assembly. End plate thickness was changed from 50mm to 35mm. The primary features of HGQ09 are listed below in Table 1.1. Changes from magnet HGQ08 are highlighted in red and italicized.

Inner Cable Strand No.	37
Inner Cable lay direction	Left Lay
Outer Cable Strand No.	46
Outer Cable lay direction	Left Lay
Cable Pre-baking	<i>None</i>
Strand Coating	<i>None</i>
Cable Cleaning	Axarel 6100
Inner Cable Insulation	25uM x 9.5mm <i>w/ 58% overlap</i> surrounded by 50uM x 9.5mm w/2mm gaps <i>w/QIX</i>
Outer Cable Insulation	25uM x 9.5mm w/ 48% overlap surrounded by 25uM x 9.5mm w/46% overlap w/QIX
Coil Curing temperature	<i>190C/135C Two step cycle</i>
Inner coil curing pressure	<i>high at 135C/ low at 190C</i>
Outer coil curing pressure	<i>high at 135C/ low at 190C</i>
Inner Coil target size	<i>+275uM, (+.011)</i>
Inner Coil MOE	<i>8GPa</i>
Outer Coil target size	<i>+275uM, (+.011)</i>
Outer Coil MOE	<i>9GPa</i>
Target Prestress	<i>75-80 MPa</i>
Coil end azimuthal Shim System	Shim ends to be same as body, tapering off toward end of saddle.
End Part Material	G-11CR

End Part Configuration	Iteration #2, 5 block design.
Splice Configuration	Internal
Voltage Tap Plan	MD-369212/MD-369259
Inter layer strip heaters	None
Outer layer strip heaters	<b>CERN version #2, double element</b>
Key extension	None
Inner coil Bearing Strips	None
Outer coil Bearing Strips	None
Collar configuration	<b>38mm long solid welded packs</b> , using new configuration without bearing strips
Collar key configuration	75mm long, phosphor bronze, positioned across collar pack gaps.
Strain Gauges	2 beam gauges on inner and outer coils, 2 capacitor gauges on inner and outer coils..
Spot Heaters	Pole turn on 2 outer coils, at lead end on parting plane turn on 2 outer coils.
End Radial Support	Collet end clamps on both ends. Aluminum exterior cans with G-11CR quadrant pieces.
Collar/Yoke Interface	Radial clearance between collar and yoke.
Quadrant Lead Configuration	Double lead with copper only cable for stabilizer
End longitudinal loading	Bullets apply load directly to coils, 2000 lbs. force per bullet. End cans are bolted to end plates longitudinally, preventing coils from contracting longitudinally.
Yoke Key Width	<b>26.5mm</b>
Strain Gauges on Skin	Yes
End Plate Thickness	<b>35mm</b>
Tuning Shims	None

Other	Return end keys mold released and replaced. Thermometers on collar/yoke keys. Axial preload bolts not instrumented.
Coil Fabrication Start Date	09/20/99
Completion Date	2/1/00

**Table 1.1** HGQ09 features.

## 2.0 Superconducting Cables

Table 2.0.1 summarizes the cable parameters used in HGQ-09. Note that the inner cable used in HGQ-09 had 37 strands with left lay pitch direction identical to HGQ-07. HGQ-01 through HGQ-05 were fabricated with 38 strand, right lay inner cable and HGQ-06 with 38 strand, left lay inner cable. Finally HGQ-08 had 37 strand, left lay inner cable but with annealed and stabrite coated strands. There were no changes in the outer cable parameters except that HGQ-08 had outer cable with annealed and stabrite coated strands.

PARAMETER	UNIT	INNER CABLE FOR HGQ-09	OUTER CABLE FOR HGQ-09
Radial width, bare	mm	15.3813	15.394
Minor edge, bare	mm	1.320	1.051
Major edge, bare	mm	1.610	1.241
Midthickness, bare	mm	1.4776	1.146
Keystone angle,	deg	1.162	0.717
Pitch Length	mm	114	102
Number of strands		37	46
Lay direction		Left	Left

**Table 2.0.1:** Cable mechanical parameters as provided by LBNL.

All cable was cleaned before insulation with Axarel 6100 in the SSC cleaning module.

## 2.2 Electrical Parameters

PARAMETER	UNIT	INNER CABLE	OUTER CABLE
R(295 K)	$\mu\text{ohms/cm}$	16.82	Data not available
R(10 K)	$\mu\text{ohms/cm}$	0.34	
RRR		49.0	
C/Sc		1.23	

**Table 2.2.1:** Cable electrical parameters as provided by BNL.

## 2.3 Cable Test Data

	INNER CABLE		OUTER CABLE	
B, T	I <sub>c</sub> , KA	J <sub>c</sub> , A/mm <sup>2</sup>	I <sub>c</sub> , KA	J <sub>c</sub> , A/mm <sup>2</sup>
6	19.140	2237		
7	14.340	1676		
8	9.539	1115		

**Table 2.3.1:** Cable test data as provided by BNL.

### 3.0 Coil Fabrication

#### 3.1 Cable and Wedge Insulation

Table 3.1.1 summarizes the cable insulation parameters used in HGQ-09. Note that the adhesive on the outer wrap of both inner and outer cable is modified polyimide (QIX) instead of QI. QIX had been introduced on the outer cable with HGQ08, but HGQ08 still had QI on the inner.

PARAMETER	INNER CABLE	OUTER CABLE
Number of wraps	2	2
<b>Inner wrap:</b> -material -adhesive -wrap structure	Kapton tape 25 $\mu\text{m}$ $\times$ 9.5 mm None Spiral wrap with 58% overlap	Kapton tape 25 $\mu\text{m}$ $\times$ 9.5 mm None Spiral wrap with 48 % overlap
<b>Outer wrap:</b> -material -adhesive -wrap structure	Kapton tape 50 $\mu\text{m}$ $\times$ 9.5 mm Modified Polyimide (QIX) Spiral wrap with 2 mm gaps	Kapton tape 25 $\mu\text{m}$ $\times$ 9.5 mm Modified polyimide (QIX) Spiral wrap with 46 % overlap

**Table 3.1.1:** *HGQ-09 cable insulation parameters.*

The wedges were insulated identically to their respective coils.

#### 3.2 Winding and Curing

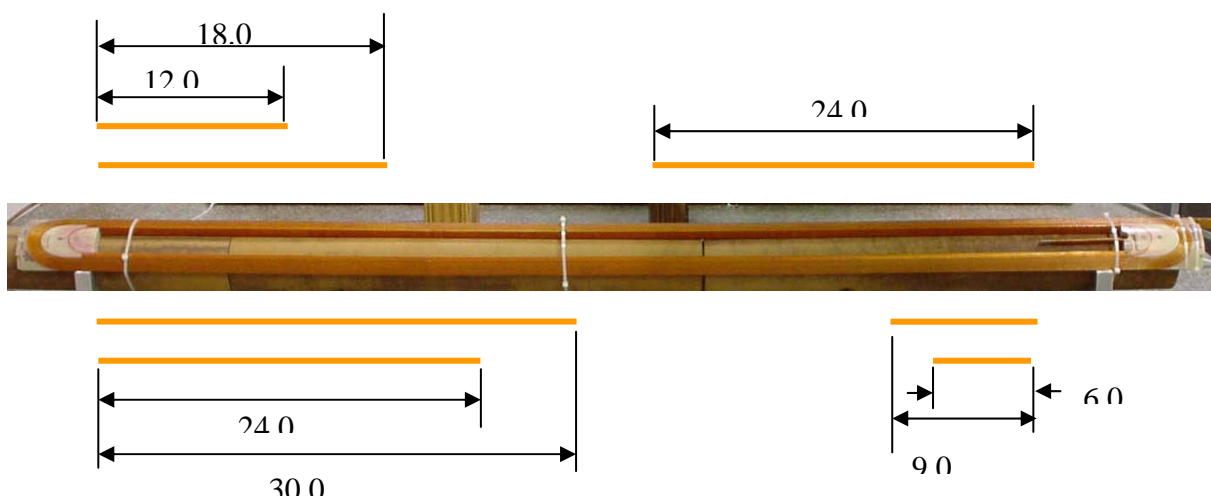
Seven inner and five outer coils were wound, cured and measured for HGQ-09. All coils had wedge breaks staggered such that the breaks would not be coincident at any longitudinal location in the same coil. From the lead end, the wedge lengths were 25", 22.6" and 19" on one side and 19", 22.6" and 25" on the other side. The gaps before curing were 0.085".

In order to test the performance of a straight ramp in inner coils, we decided to use two inner coils with straight ramps and two with the traditional curved ramp. Turn to turn shorts were detected during end-compression in three of the seven inner coils. It was later found that these shorts were due to pop strands (in HGQi-062 the pop strand was found between 12<sup>th</sup> and 13<sup>th</sup> turn of RE; in HGQi-063 it was found between 11<sup>th</sup> and 12<sup>th</sup> turn of LE, and HGQi-066 is still under investigation)

To achieve a uniform size distribution along the length of the coil, parting plane Kapton shims were placed during curing at the parting planes of both inner and outer coils. Figs. 3.2.1 and 3.2.2 show the shim plan for outer and inner coils respectively used in HGQ-09.



**Fig. 3.2.1:** The parting plane shim used in HGQ-09 inner coils during curing to minimize the variation of the size along the length of the coil. Each Kapton layer is  $25\ \mu\text{m}$  (or 1 mil) thick.



**Fig. 3.2.2:** The parting plane shim used in HGQ-09 outer coils during curing to minimize the variation of the size along the length of the coil. Each Kapton layer is  $25\ \mu\text{m}$  (or 1 mil) thick.



### 3.3 Coil Measurements

#### 3.3.1 Coil Straight Section

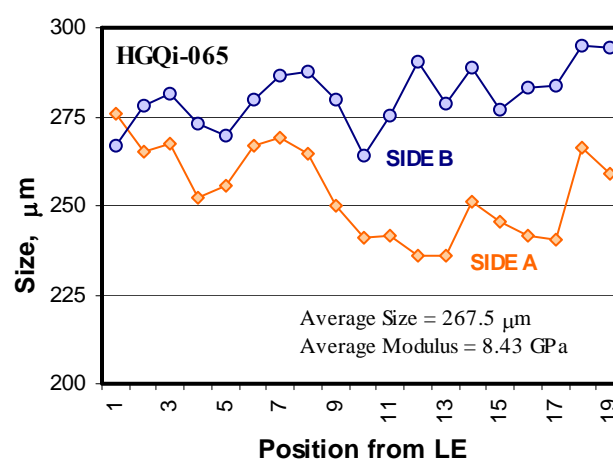
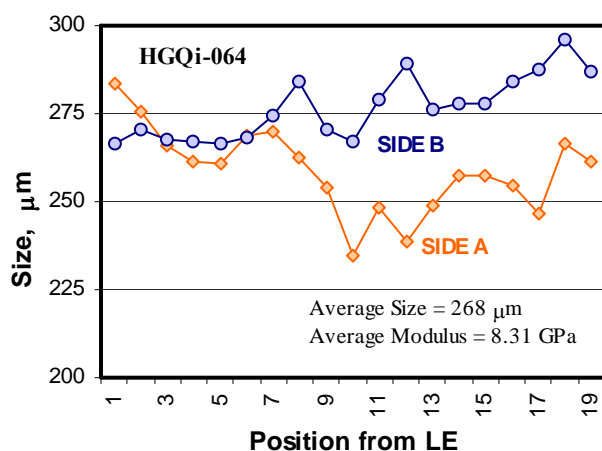
The coil azimuthal size and modulus measurements were taken over a range of pressures, 55 to 100 MPa. The design pressure for both the coils at room temperature is about 80 MPa. Coils were measured with a 3 inch gauge length along the straight section of the magnet, from LE to RE. The ends of the magnet were measured separately using end-compression units and will be discussed in the next section. Table 3.3.1 lists the coils used in HGQ-09 and their corresponding average size and modulus.

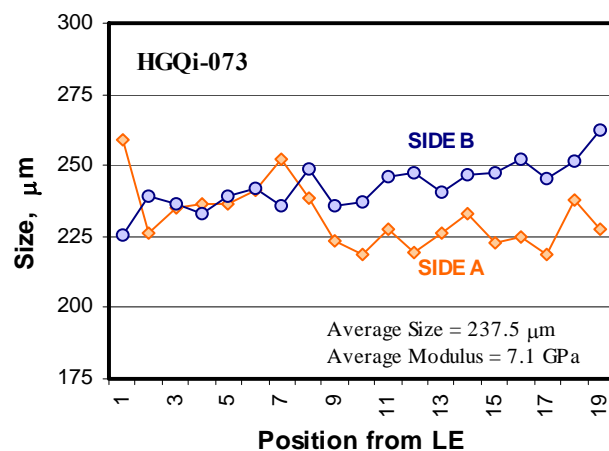
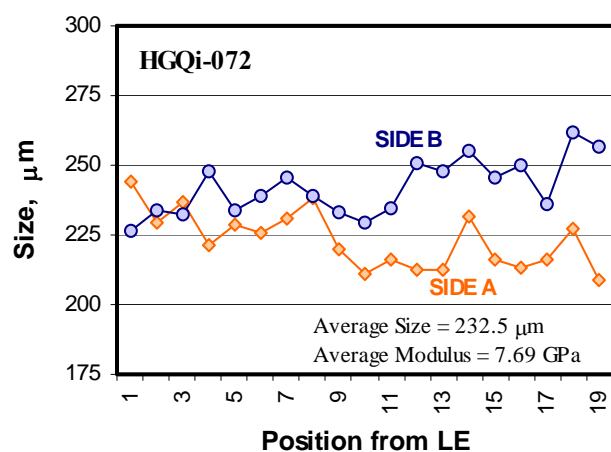
Coil Numbers	SIDE A $\mu\text{m}$	E(A) GPa	SIDE B $\mu\text{m}$	E(B) GPa
HGQi-064 (straight ramp)	259	8.29	277	8.33
HGQi-065 (straight ramp)	254	8.78	281	8.08
HGQi-072 (curved ramp)	223	7.74	242	7.64
HGQi-073 (curved ramp)	232	7.12	243	7.08
HGQo-058	277	8.69	257	9.14
HGQo-059	262	8.69	243	9.24
HGQo-060	268	8.41	265	8.61
HGQo-064	294	8.82	277	9.30

**Table 3.3.1:** HGQ-09 coil body size and moduli.

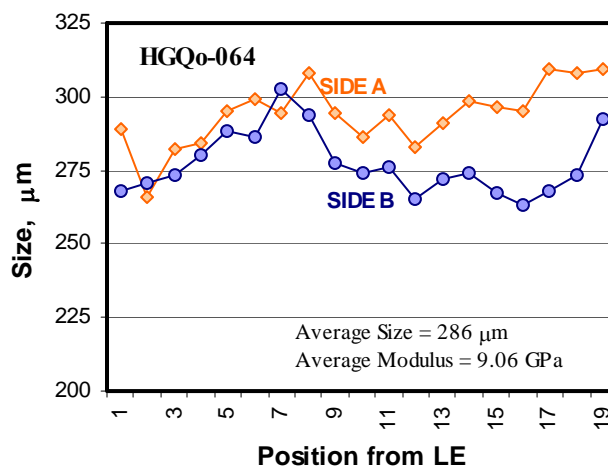
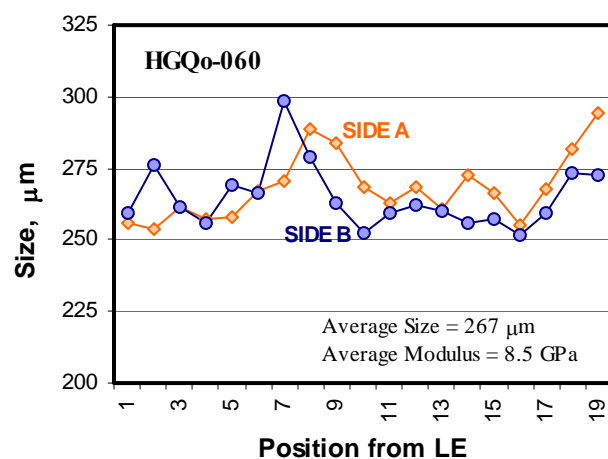
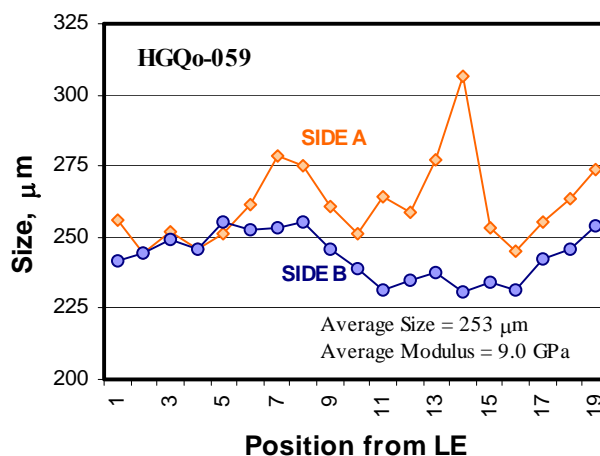
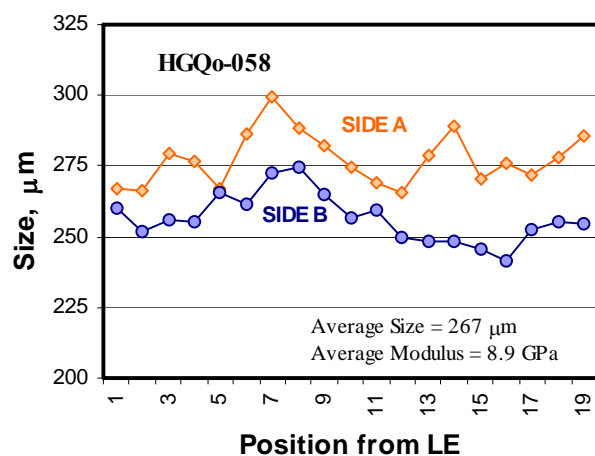
Note that the target size for both inner and outer coils is +275  $\mu\text{m}$ .

Variation of the size along the length of the coils is shown in Figs 3.3.1 and 3.3.2. Note that Side A is the “first wound” side of the coil and Side B is the side with the lead extending from the end of the saddle.





**Figure 3.3.1:** Variation of size along the length of inner coils.



**Figure 3.3.2:** Variation of size along the length of outer coils.

### 3.4 Coil Shimming

#### 3.4.1 Coil Straight Section

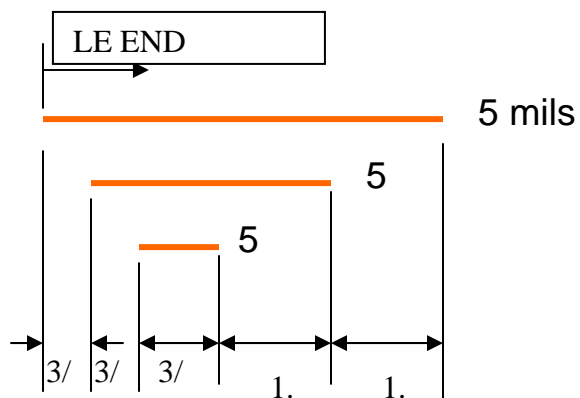
The target pre-stress for HGQ-09 is about 75-80 MPa. This corresponds to a nominal coil size of +275  $\mu\text{m}$  for both inner and outer coils. The inner coil size varied from 223 to 281  $\mu\text{m}$  with an average of 251  $\mu\text{m}$ ; whereas the outer coil size varied between 243 to 294  $\mu\text{m}$  with an average of 268  $\mu\text{m}$ . The following table lists the shim sizes used in HGQ-09:

I/O	Quadrant	Coil #	Coil Size $\mu\text{m}$	Pole Shim $\mu\text{m}$	PP Shim $\mu\text{m}$	Target $\mu\text{m}$	Shimmed Coil Size $\mu\text{m}$
Inner	1A	i-064	259	0	25	275	284
Inner	1B	i-064	277	0	25	275	302
Inner	2A	i-072	223	0	25	275	248
Inner	2B	i-072	242	0	25	275	267
Inner	3A	i-065	254	0	25	275	279
Inner	3B	i-065	281	0	25	275	306
Inner	4A	i-073	232	0	25	275	257
Inner	4B	i-073	243	0	25	275	268
Outer	1A	o-064	294	0	0	275	294
Outer	1B	o-064	277	0	0	275	277
Outer	2A	o-060	268	0	0	275	268
Outer	2B	o-060	265	0	0	275	265
Outer	3A	o-058	277	0	0	275	277
Outer	3B	o-058	257	0	0	275	257
Outer	4A	o-059	262	0	0	275	262
Outer	4B	o-059	243	0	0	275	243

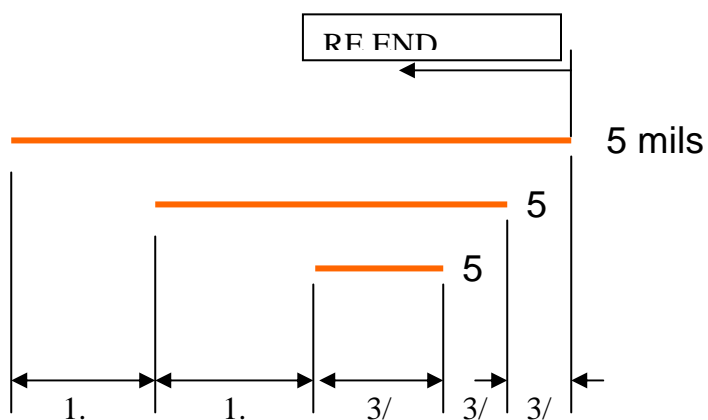
**Table 3.4.1:** Kapton shimming used in the coil straight section.

#### 3.4.2 Coil Ends

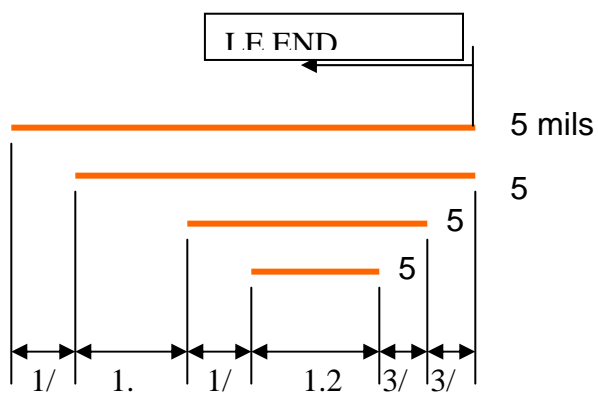
The end-shimming was done identical to HGQ06-8. Figs. 3.4.1 through 3.4.2 shows the shim plan.



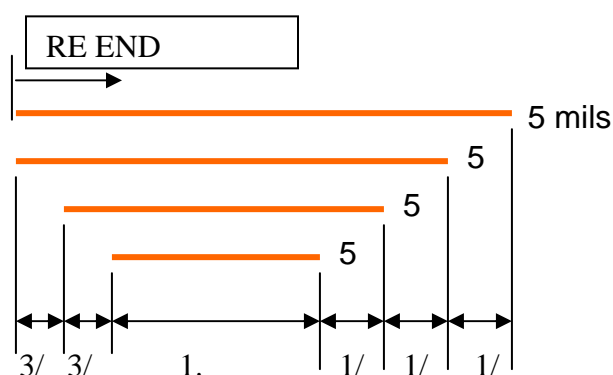
**Figure 3.4.1:** End-Shimming for inner coil LE



**Figure 3.4.2:** End-Shimming for inner coil RE.



**Figure 3.4.3:** End-shimming for outer coil LE.



**Figure 3.4.4:** *End-shimming for outer coil RE.*

### 3.5 Voltage Taps and Spot Heaters

Voltage taps were mounted according to the drawing number 5520-MD-369212 for inner coils and 5520-MD-369259 for outer coils. End-compression tests with a 5 inch pusher bar were done at 85 MPa on all HGQ-09 coils after installing the voltage taps to check for turn-to-turn shorts. As discussed in the winding and curing section, we detected turn-to-turn shorts in three of the seven inner coils. None of the other coils had turn-to-turn shorts.

During assembly two additional voltage taps were added on either side of the spot heaters mounted between the 16<sup>th</sup> turn and the G-11 spacer (ramp splice) on outer coils, HGQo-060 (Quadrant II) and HGQo-058 (Quadrant III).

Spot heaters were installed between the end-saddle and the last turn during winding on outer coils, HGQo-064 (Quadrant I) and HGQo-059 (Quadrant IV). Spot heaters were also installed between the 16<sup>th</sup> turn and the G-11 spacer in outer coils, HGQo-060 (Quadrant II) and HGQo-058 (Quadrant III) later during coil assembly.

## 4.0 Coil Assembly

### 4.1 Coil Arrangement

Coils in HGQ magnets are arranged to obtain the most uniform possible preload distribution between quadrants, given the coils available. The coil arrangement is shown in Figure 4.1.1. The amount of shim placed at each pole and parting plane is shown in red (positive numbers indicate kapton added, negative numbers indicate kapton removed). Shims are frequently added to (or removed from) the parting plane and/or pole area to achieve the “target” azimuthal coil size and hence the desired preload. See also section 3.4 for a discussion of coil shimming.

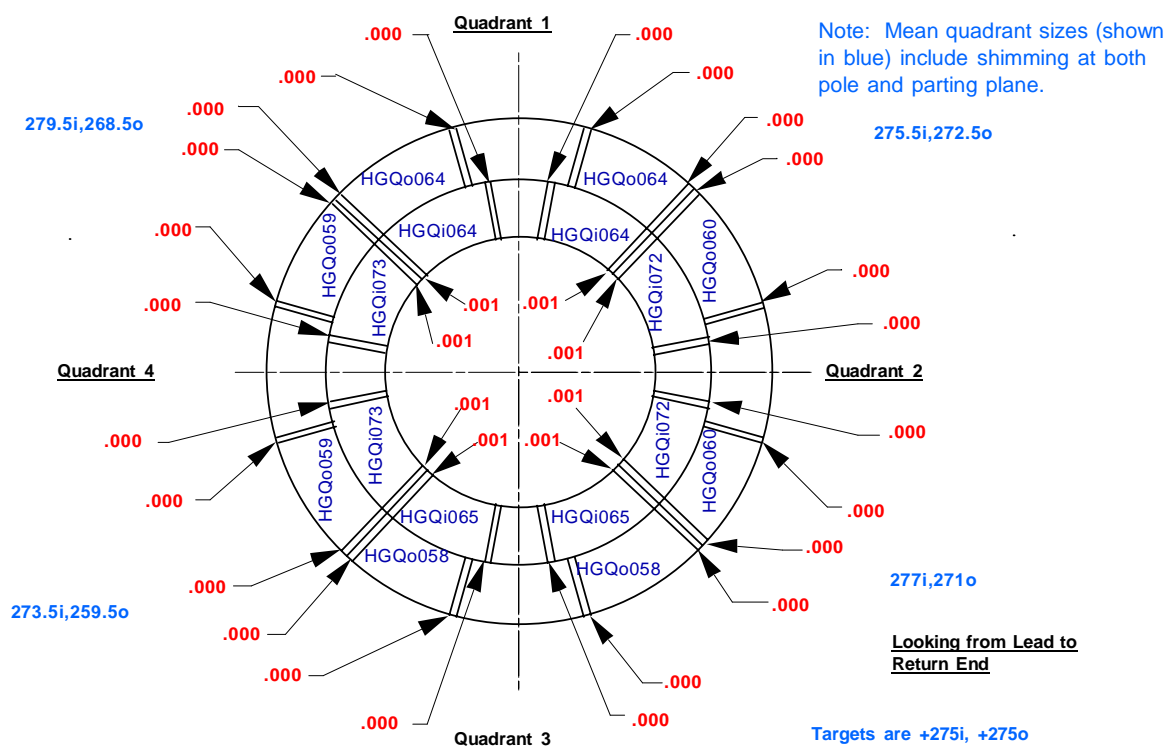


Figure 4.1.1 HGQ09 Coil Arrangement

### 4.2 Splice

The pole turn of each inner/outer coil pair needs to be spliced together. The internal splice configuration is used for HGQ-09. Splices are 114 mm long, which is approximately equal to the cable transposition pitch. Areas to be spliced are preformed, and filled with solder before the coil is wound. The filled, or “tinned” sections are then spliced after the coils are assembled on the mandrel. A cooling fixture was attached to the “coil” side of the splice to prevent the coil from being heated excessively. The maximum

temperature for the turn next to the heater during the splicing processes was about 60C/140 F.

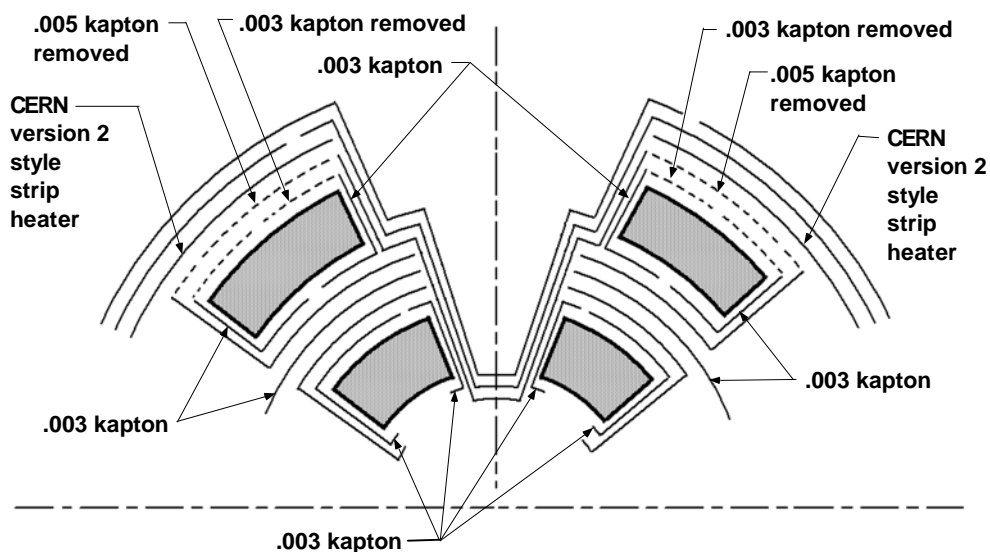
A 30 mil metal shim was placed into the splice fixture to achieve uniform compression for the cable strands during splicing. All splices were insulated with two layers of Kapton tape, one layer of 25um thick  $\times$  9.5 mm wide surrounded by one layer of 50um thick  $\times$  9.5 mm wide. Both layers are spiral wrapped with 2 mm gaps. The second layer is wrapped directly on top of the first layer, leaving uncovered bare cable in the 2mm gaps. Axial and radial cooling channels were made in the G11CR spacers as well. All coils were surrounded by ground insulation after splicing.

### 4.3 Ground Wrap System

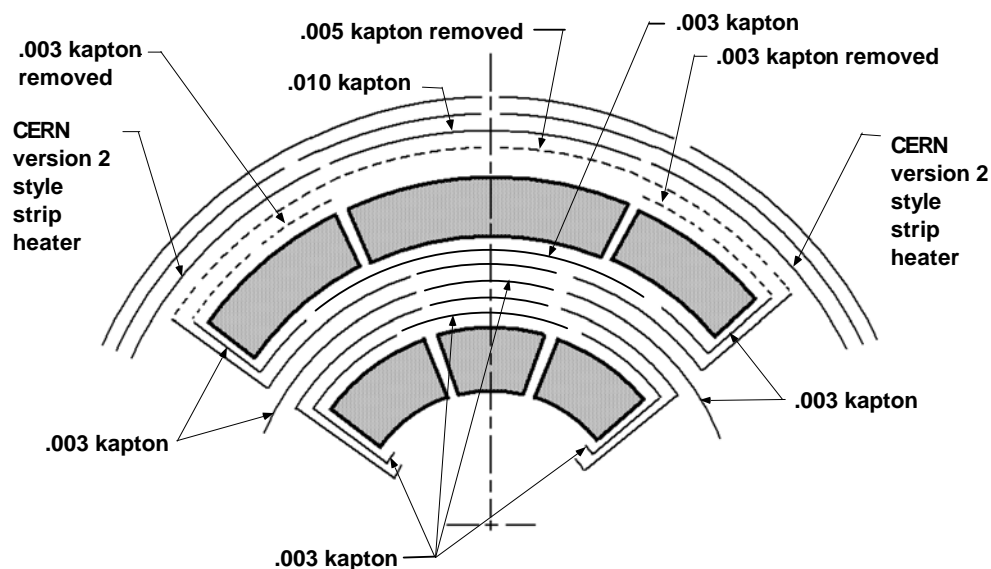
**The coil insulation and ground wrap systems (body and ends respectively), for HGQ09 are shown in Figures 4.3.1 and 4.3.2. All layers of kapton are .005 inch (125um) thick unless otherwise specified in the figures. One layer of .005 inch (125um) kapton and one layer of .003 inch (75um) kapton were removed between the outer coil and the collars to allow room for the .008 inch (200um) thick strip heater (CERN style version #2). One layer of .003 inch thick kapton was added between the inner and outer coils to take the place of the inter layer strip heater. The original design allowed for a strip heater between the inner and outer coils, but not between the outer coils and collars.**

**The internal “flaps”, where the inner coil layers wrap around the inner surface of the inner coils, were left in place on HGQ09, at both the pole and parting plane. These flaps are used to provide longer resistive paths between components with different electrical potentials, but were removed on HGQ08. They will probably also be removed on the MQXB prototype and production long magnets to provide more helium flow around the beam tube.**

**A complete description of the ground wrap system for HGQ09 is shown in drawing 5520-MC-369486.**



**Figure 4.3.1 HGQ09 Body Coil and Ground Insulation System**



**Figure 4.3.2 HGQ09 End Coil and Ground Insulation System**

## 4.4 Strip Heaters

Quench protection (strip) heaters have, at various times, been placed in two different positions in High Gradient Quadrupoles, radially between the inner and outer coils, and between the outer coils and collars. Several different designs have also been used.

HGQ09 has no heaters between the inner and outer layers. CERN style version 2 heaters were used between the outer layers and collars. These heaters are the “double element” style (turnaround on



return end, so elements are not jumpered across the back of return end saddles). They have stainless steel elements, .001 inch (25um) thick, .630 inches (16mm) wide, copper plated on one side. The copper is etched away intermittently over 4.00 inch ( 101.6mm) lengths, exposing the stainless, with 4.00 inch (101.6mm) lengths of copper plated areas between them. The stainless/copper element is sandwiched between (and bonded to) two pieces of .004 in. (100 micron) thick kapton. They were made for HGQ magnets at CERN. The strip heaters are described in detail in drawing #5520-MB-369369.

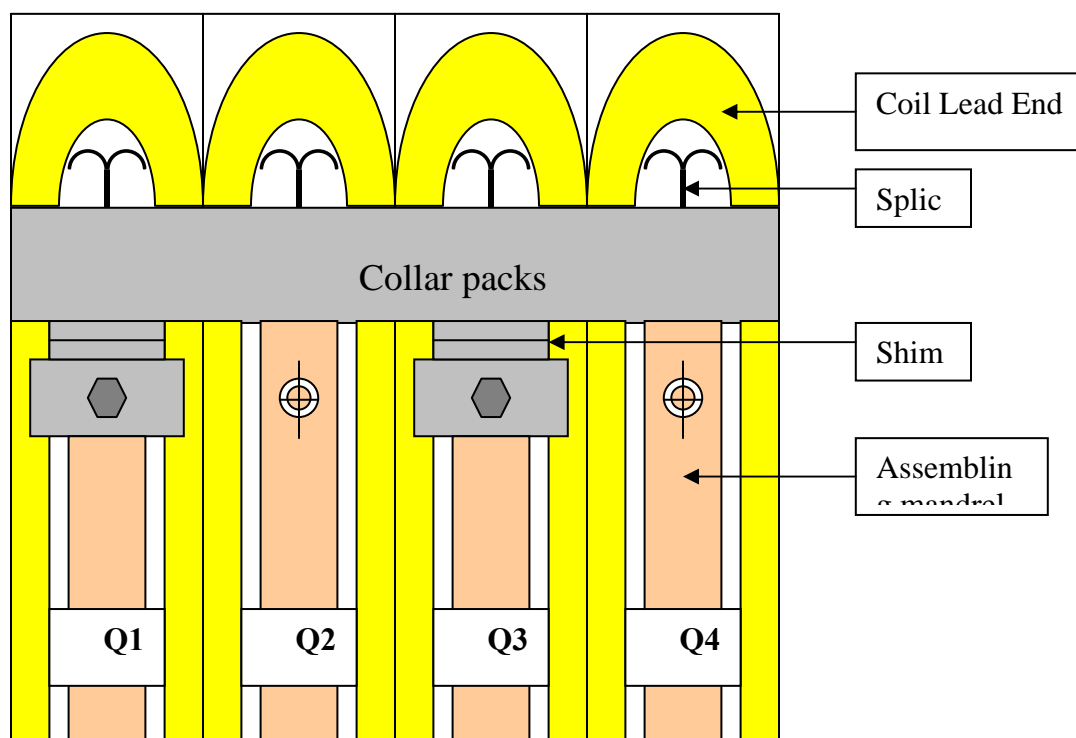
## 5.0 Collaring and Keying

### 5.1 Collaring and Keying History

Longitudinal alignment for the inner and outer coils layer-to-layer and quadrant-to-quadrant on the mandrel is required because:

- stresses in the internal splice need to be minimized.
- the splice is soldered before keying
- “key extensions” have been eliminated from the design

**To ensure that the splices are aligned properly, the coils are assembled so that the back end of the lead end keys of all four quadrants in both layers are coplanar. The back ends of the inner coil keys on the Return End are then “cut to fit” at assembly to make them coplanar (quadrant-to-quadrant variations in length within the same layer are small enough to ignore). The first collar pack behind the splices (or below the splices, as the magnet is hung with the lead end up for collaring), has been used as the alignment base for the quadrants.**



**Figure 5.1.1.** Quadrant alignment.

**The collar packs in the magnet straight section are assembled by hand starting from the Return End. No friction problems between collar packs were observed during assembly.**

Laminations with a new geometry (pole areas wider by the size of two bearing strips, with the bearing strips removed) have been used for the welded collar packs.

Each collar pack is 25 laminations long, (~38.6 mm total length). These packs are half the length of the packs from previous short models. Packs are made with a “large” lamination on each end, creating a gap between each collar pack in each quadrant, where a “small” lamination is missing. Cutting the pack length in half increases the number of gaps by a factor of 2, allowing more paths for heat flow. Packs at the lead end next to the coil keys have 36/35 laminations for better longitudinal end support. Also, the last installed packs have 25/24 laminations so no gaps appear at the end of the collared section, against the end parts.

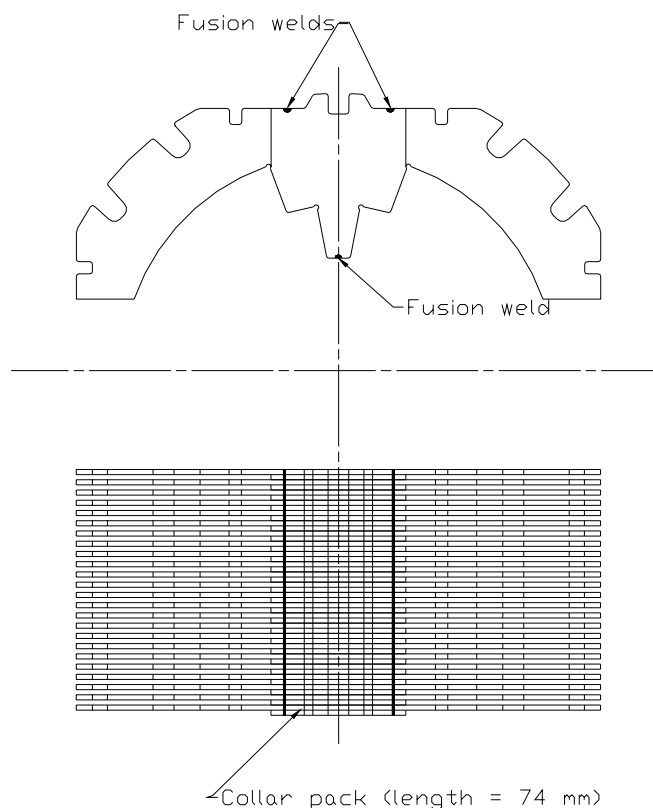


Figure 5.1.2. Collar pack.

Packs with bearing strips, similar to those used in HGQ07, were used as capacitor gauge packs. The instrumentation packs for HGQ09 are approximately in the middle of the straight section. The beam pack is adjacent to the capacitor gauge pack.

## 5.2 Keying

The magnet has been collared and keyed once. The collared assembly is “massaged” at 500, 1500 and 3000 pump psi of the main cylinder pressure (MP), partially keyed by hand at MP=5750 pump psi. Final keying was done at MP=8250 pump psi using 4000 pump psi of the key cylinder pressure (KP).

Collaring keys were 3 inches long. The keying operation was performed with keys inserted across the collar pack boundaries. The key-pack overlap is approximately 0.7 inches, half the pack length. No problems were observed because of this during keying.

No shorts to ground during keying were discovered. Figure 5.2.1 shows the pack locations along the magnet body and the keying procedure in detail.

[illegible]

Figure 5.2.1 Map of packs and keying procedure.

### 5.3 Final pressures

Location of the gauges shows on Fig. 5.3.1.

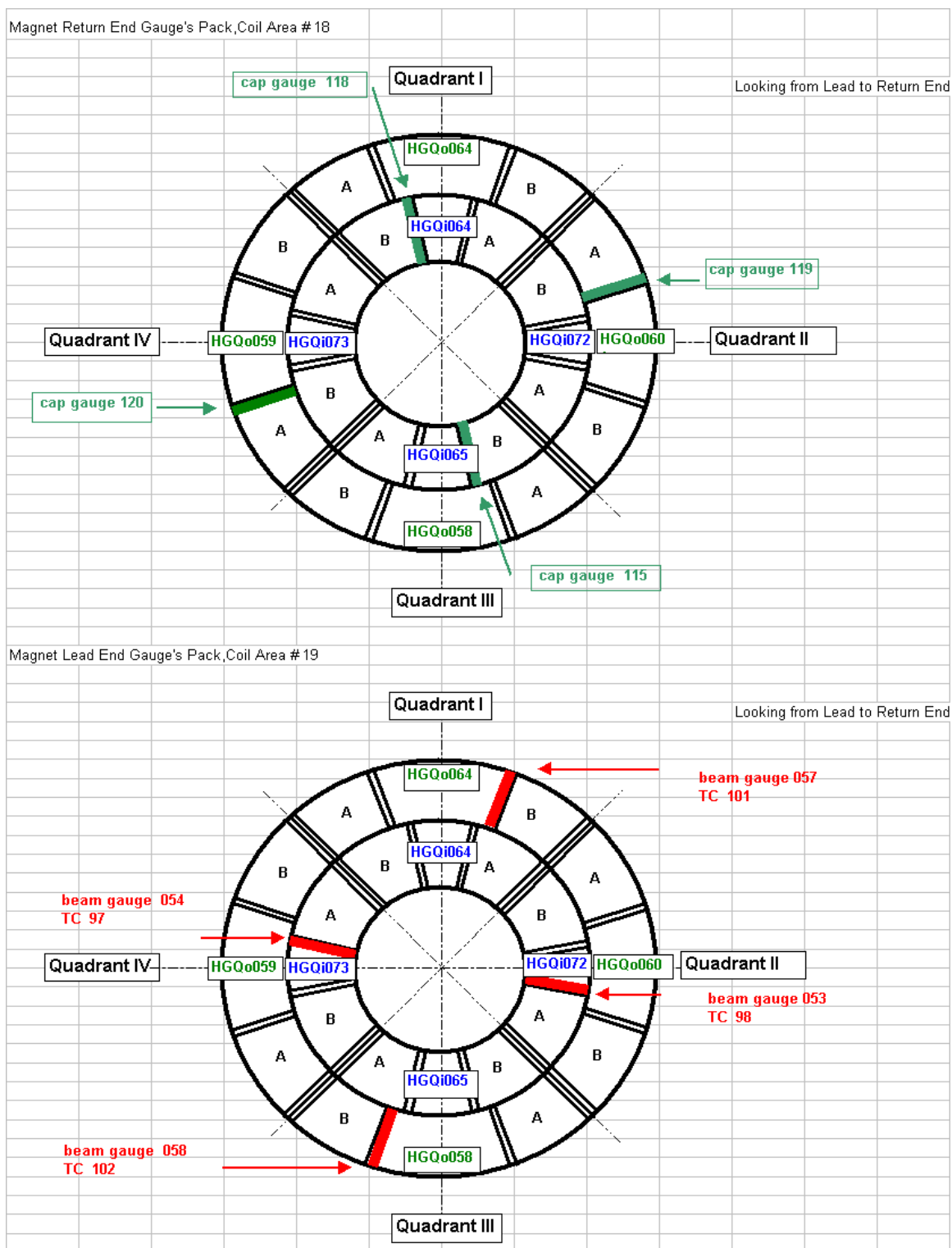


Figure 5.3.1 Gauge pack location.

The gauge readings during magnet construction are summarized below:

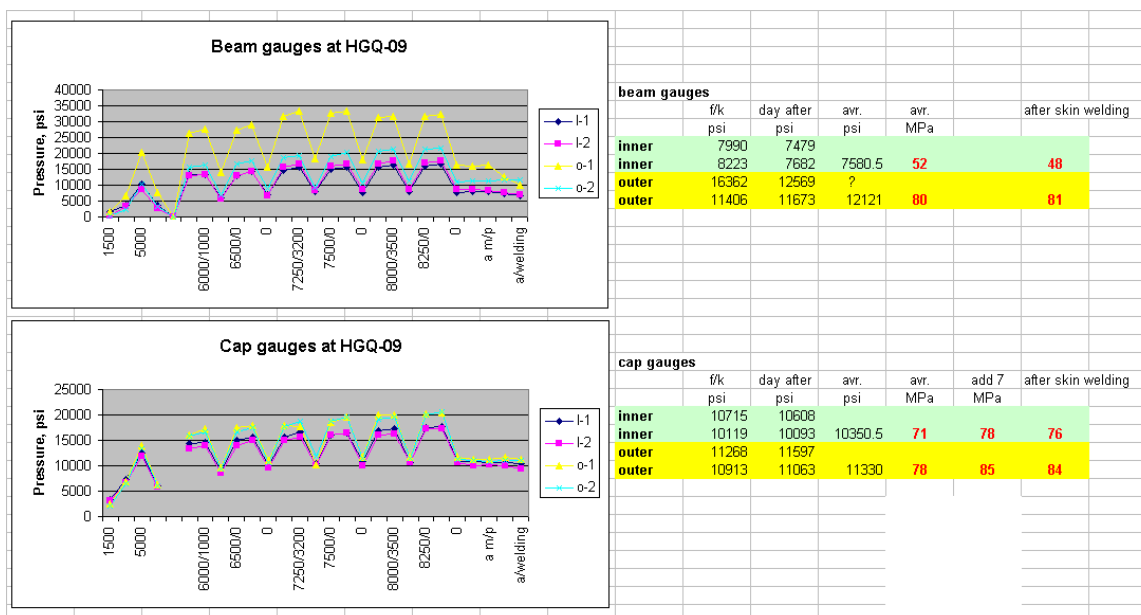


Figure 5.3.2 Gauge History.

The new inner beam gauge design (by Sunil Yadav) was used in the magnet. All readings were similar except the outer beam gauges, which had a large variation. The prestress is 91 MPa for inner and 100 MPa for outer coils respectively.

The coil size target for HGQ09 was 275  $\mu\text{m}$  with allowed variations of  $\pm 25 \mu\text{m}$  on mean coil size and  $\pm 25 \mu\text{m}$  on within coil variations, making the total tolerance on coil size from “the largest point on the largest coil” to “the smallest point on the smallest coil”  $\pm 50 \mu\text{m}$ .

Good agreement was reached between FEA predictions and preload measurements.

## 5.4 Mechanical measurements

The OD measurement data for the collared coil assembly is shown in Figs. 5.4.2-5.4.3.

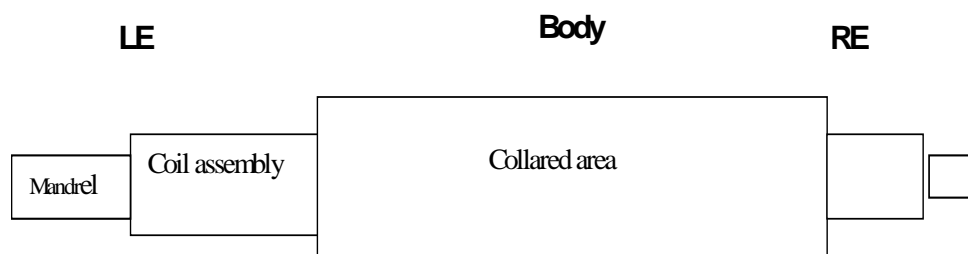


Figure 5.4.1. Collared coils with coil assembly on the mandrel.

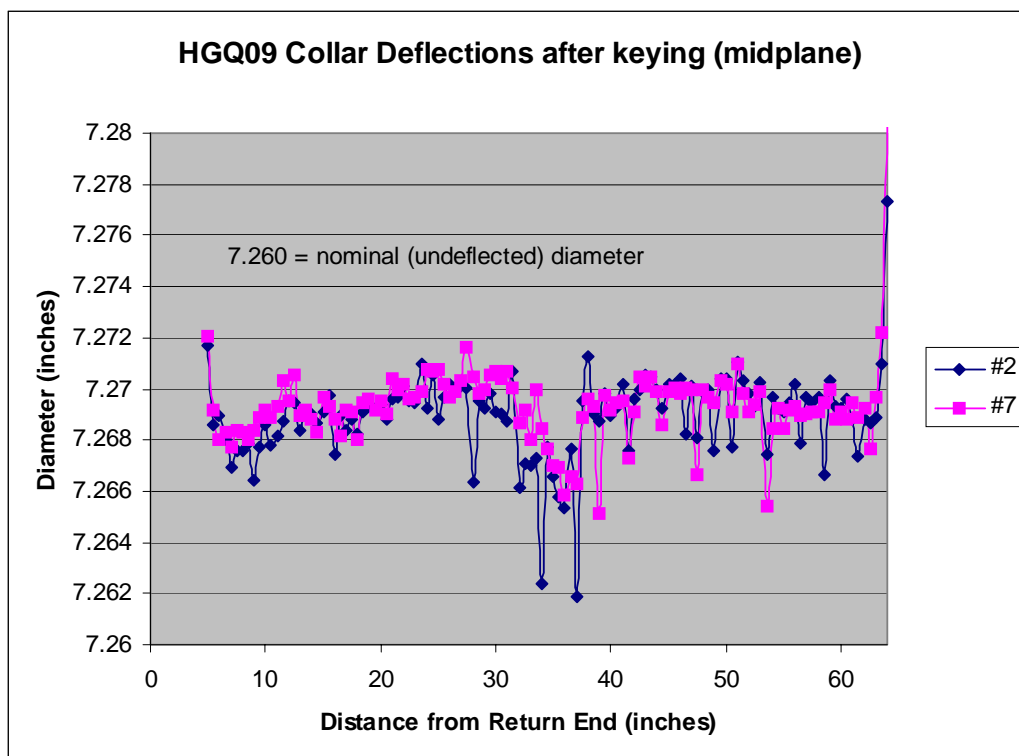


Figure 5.4.2 Collared coil deflections at midplane region after keying.

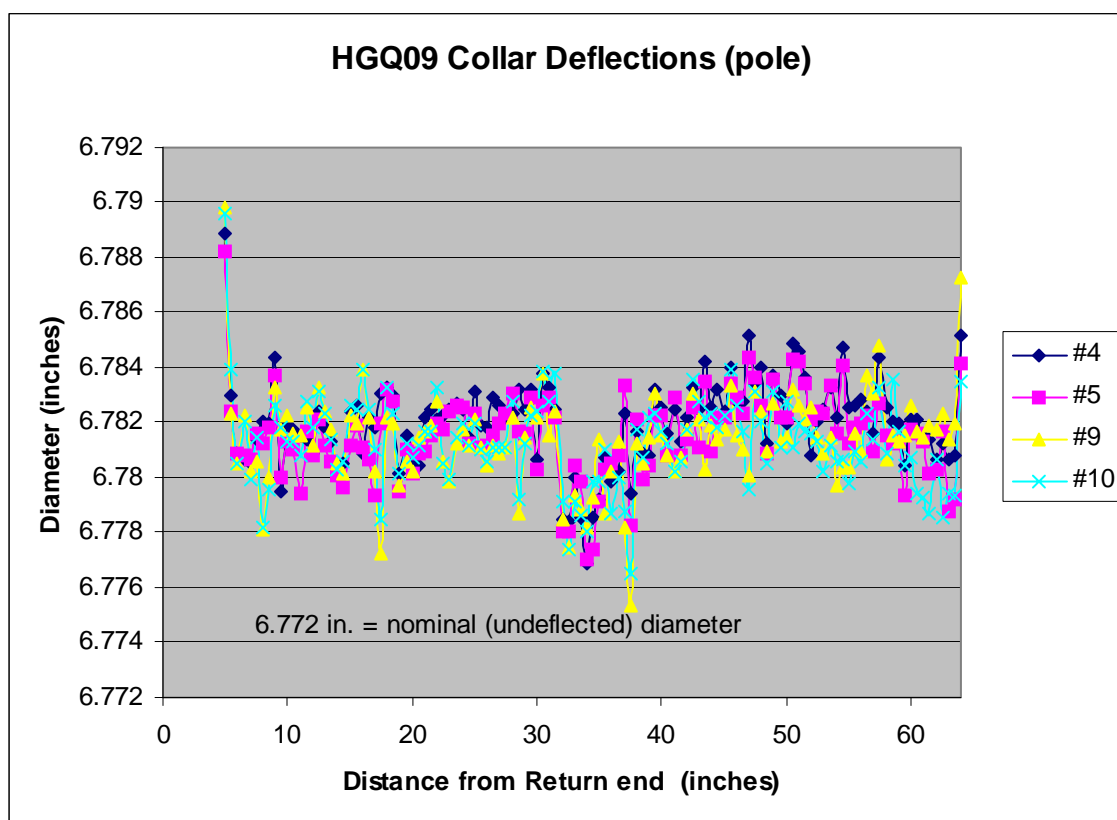


Figure 5.4.3. Collared coil deflections at pole region, pos #4,5,9,10

## 6.0 End Clamps

### 6.1 Installation Procedure:

HGQ-09 has end cans at both the Lead (LE) and Return (RE) ends. The LE can is 9.833 inches long and the RE can is 5.194 inches long. G-11 filler cones were used. Fuji film tests were performed before the final installation. The results of the Fuji film readings showed that there is a uniform radial pressure distribution from the transition region to the end-saddle for both LE and RE.

### 6.2 Measurements and Shimming:

The medium range Fuji film thickness is 4 mil and the Fuji film readings were taken without removing any designed ground insulation layer. The pi-tape measurements and film readings showed the desired results. It was then decided to increase the thickness of radial ground insulation surrounding the outer coil by 5 mils at both ends from the original design. (Fuji film and pi-tape measurements of most short models have shown an increase of either 3 or 5 mils to be necessary). The radial deflection of the aluminum end cans according pi-tape measurements (with the extra 5 mils of insulation included) are shown below in Figure 6.2.1 (target diameter change from FEA, was 10 ~ 12 mil at LE and 8 ~ 12 mil at RE).

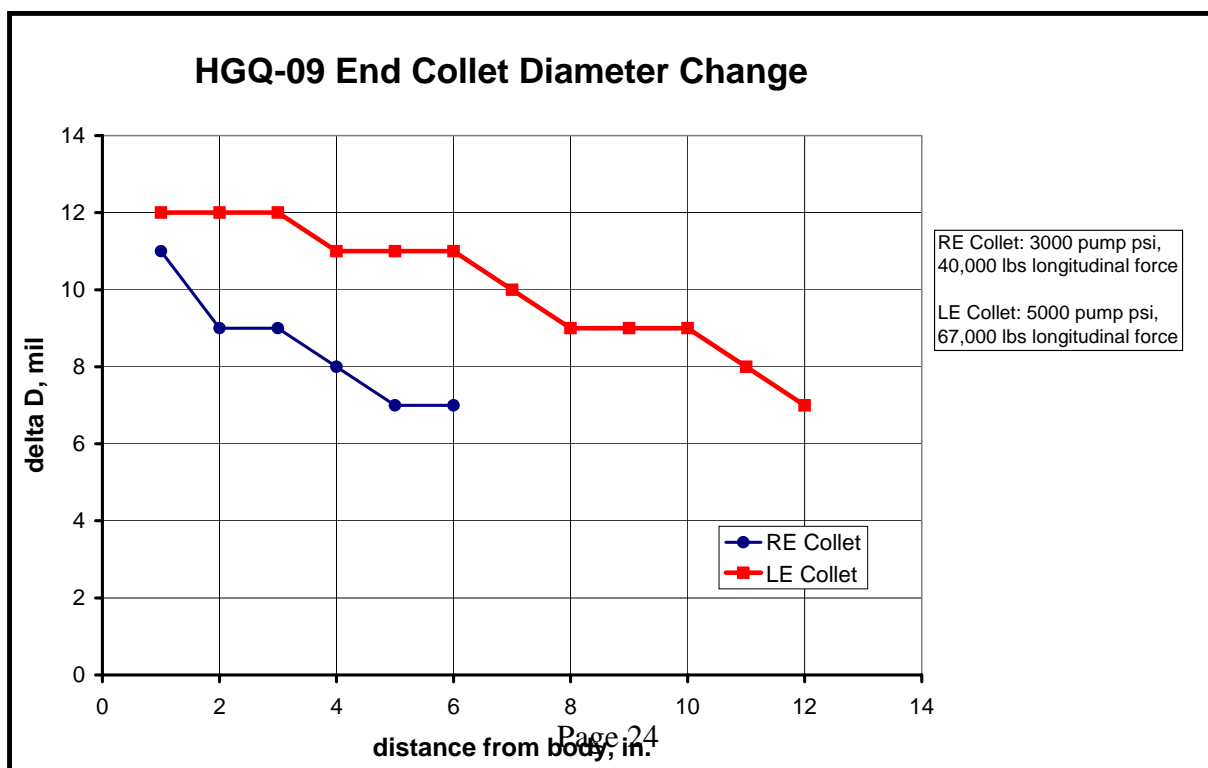
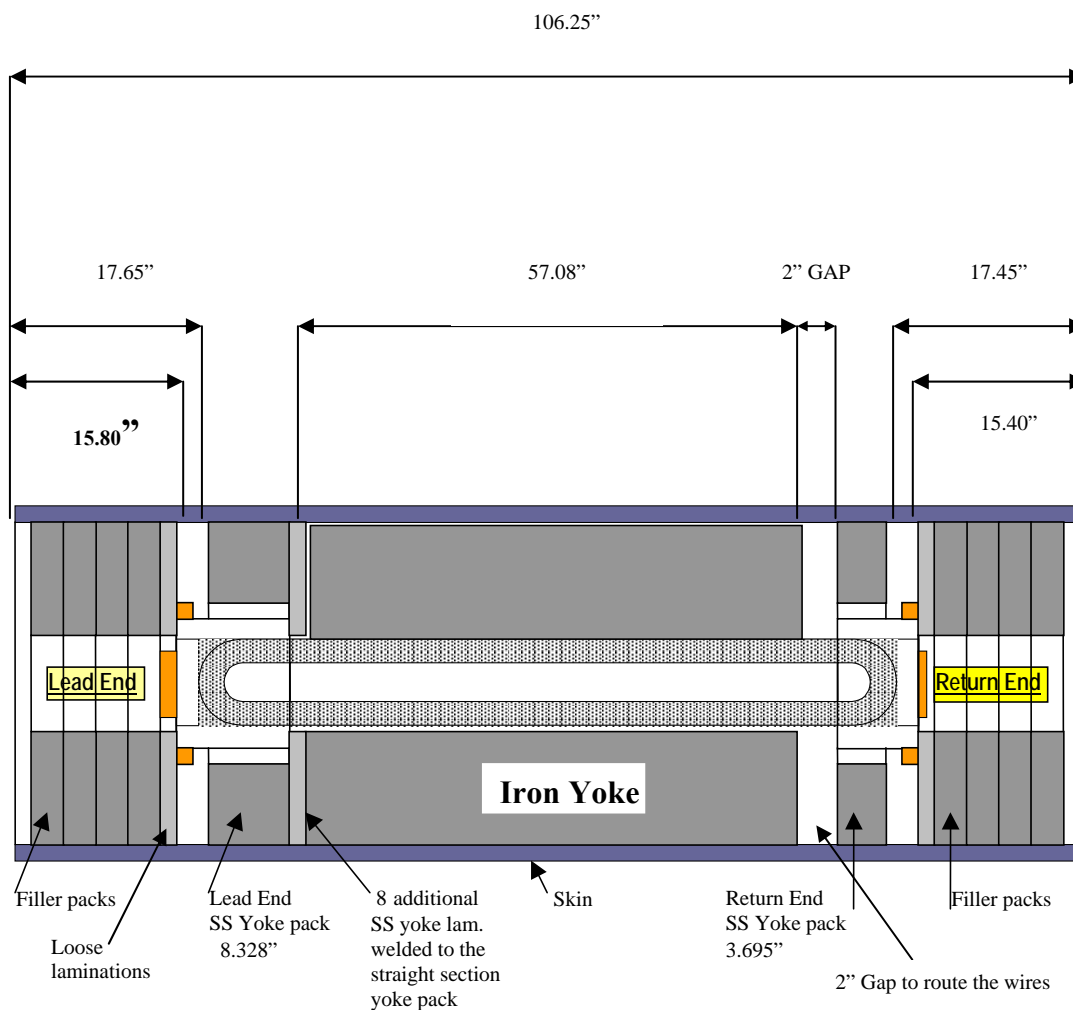




Fig 6.2.1: Aluminum End Can Radial Deflection

## 7.0 Yoke and Skinning

### 7.1 Assembly Configuration:



**Fig 7.1.1: HGQ-09 Yoke Assembly Configuration**

**All lamination packs were fusion welded longitudinally in 7 places (5 welds on outer surface and 2 welds on inner surface). Instead of 2 loose and 2 welded stainless steel laminations that were usually added to the lead end side of straight section yoke pack, 8 stainless steel laminations were welded to the lead end side of the straight section yoke pack for HGQ-09, as was done for HGQ-08 and HGQ-07. Stainless steel modified yoke laminations were used for RE and LE. These laminations were modified at the pole by EDM process to fit over the LE and RE can. The above Figure 7.1.1 shows the length and the layout of the yoke laminations during assembly.**

## **7.2 Welding:**

The skin alignment key was 26.5 mm wide for HGQ-09. The key width was increased from 24 mm to 26.5 mm for HGQ-09. The goal of this increase was to eliminate any possible buckling of the yoke laminations during the complete welding of HGQ-09. During the welding of HGQ-09, the weld preps were 100% filled with weld. There was a risk that the weld shrinkage will be over the allowed amount. This precaution was taken after similar results were monitored during mechanical model welding tests. The weld prep of the skin and skin alignment keys was modified from V to J groove to optimize the weld penetration specs.

Because the volume of the weld prep increased, the amount of filler passes necessary to fill the groove was also increased.

The 26.5-mm wide skin alignment key leaves a gap of 120 mils between the upper yoke and upper the skin; also a 120 mil gap between the lower yoke pack and skin alignment key. The total gap allowed for weld shrinkage is 240 mils. The magnet was compressed at 600 PSI during welding. The magnet was compressed in the contact tooling with a hydraulic pressure of 600 PSI, corresponding to a force of about 8000 lbs. (3600 kg) per pusher or 16000 lbs./ft (23700 kg/meter) of magnet length. A pressure above 500 PSI must be applied to completely collapse the springs in the wheel units of the bottom tooling.

After each pass, the distance between the top and bottom pushers was measured from both the north and south side of the press all along the length of the magnet. The goal of these measurements is to monitor the shrinkage of the skin during welding. The total shrinkage does not have to be over 0.240 inch; if it is, there is a probability that the yoke pack laminations will buckle from the excessive forces introduced by the shrinkage of the skin.

During the twist study, it was confirmed that the south torches are moving faster than north torches, resulting in a consistent twist for all the previous HGQ cold masses except HGQ-07, where the twist was significantly reduced by the forward offset of the south

torches by 2 inches. The same technique was repeated for the HGQ-09 cold mass to eliminate any twist that can be caused by unsynchronized welding of the north and south side of the cold mass.

The first pass was a fusion pass. Then, consecutively, four filler passes were applied. It is known from HGQ-08 and mechanical models that the J groove requires more weld material to be filled.

The below graph shows these results:

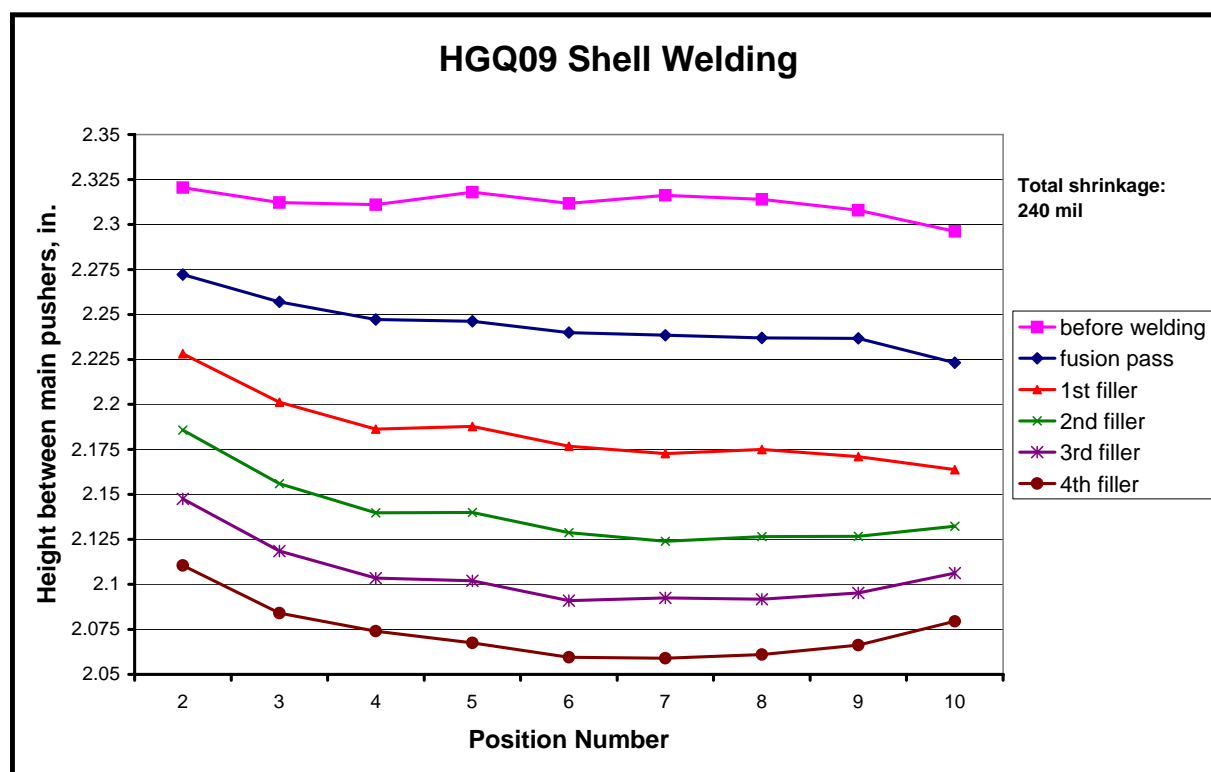


Fig 7.2.1: Weld Shrinkage for HGQ-09 with 26.5 mm key

After the welding was completed, the magnet was transported back to IB3 from ICB. The skin was cut to the exact length. After the routing of instrumentation wires was completed, the end plates were welded. The weld coupons showed a 100% full penetration of weld.

### 7.3 OD and Twist Measurements:

The skin OD measurements were taken at different angles after the end plate welding. The following graph shows the results of this measurement:

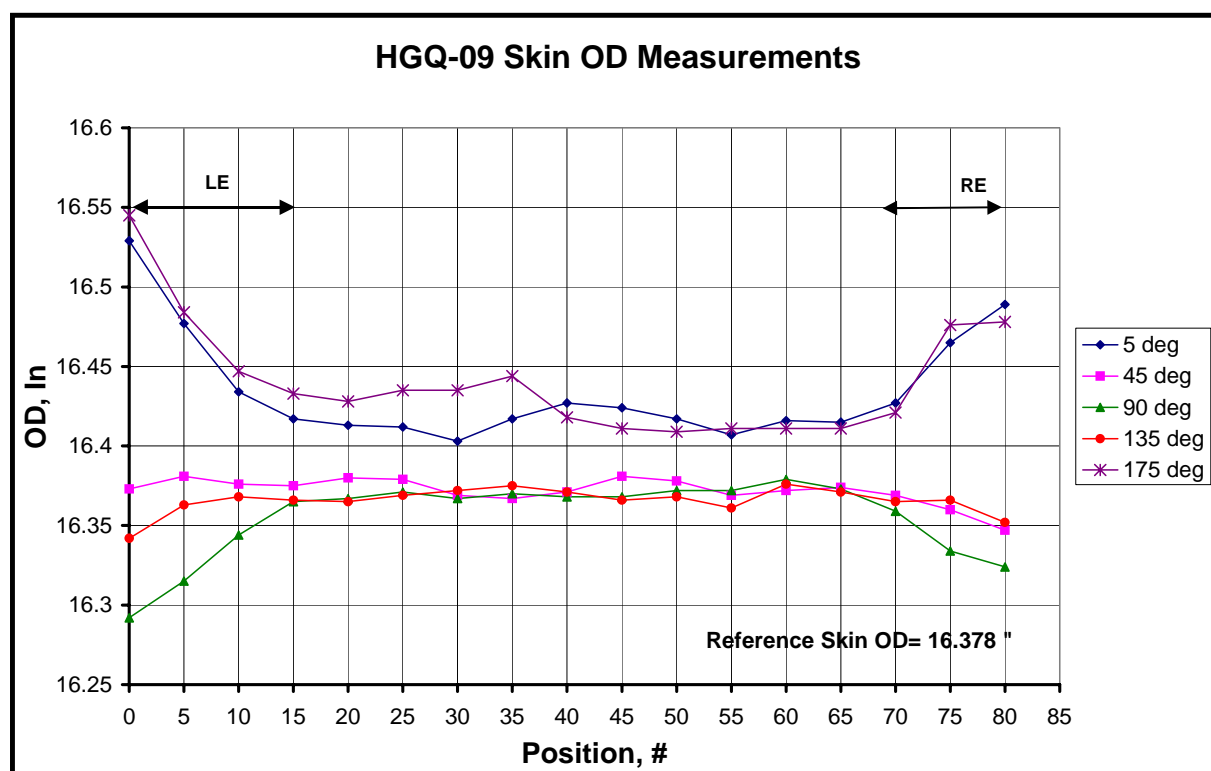


Fig 7.3.1: Skin outer diameter according to micrometer measurements taken at different angular positions between skin alignment keys

The twist in the cold-mass assembly after welding the skin and the end plates was measured with a twist-measuring device on a granite table at IB3. The twist was measured to be 0.0007 milli-radian per meter in the straight section of the magnet. The allowable twist for HGQ Cold Mass has to be less than 0.3 milli-radian per meter. The

twist in HGQ-01 was 4.67 milli-radian per meter, for HGQ-02 it was 0.6 milli-radian per meter, for HGQ-03 it was 1.0 milli-radian per meter, for HGQ-05 it was measured as 0.9 milli-radian per meter. The twist was 0.95 milli-radian per meter for HGQ-06 and with the corrective actions, the twist was reduced to 0.18 milli-radian per meter for HGQ-07. It was measured 0.04 milli-radian for HGQ-08. The direction of the twist is same in all the seven magnets, that is, clockwise, looking from LE to RE. Fig. 7.3.2 shows the twist measurements done with the twist measuring device in milli-radians.

The offset of the torch technique did work well with the mechanical model and HGQ-07 and HGQ-08. The technique is rechecked one more time with the HGQ-09 cold mass. It can be said that the twist problem was thoroughly solved for the 2-meter model magnets. The welding press and system has to be checked and repaired before the prototype manufacturing starts.

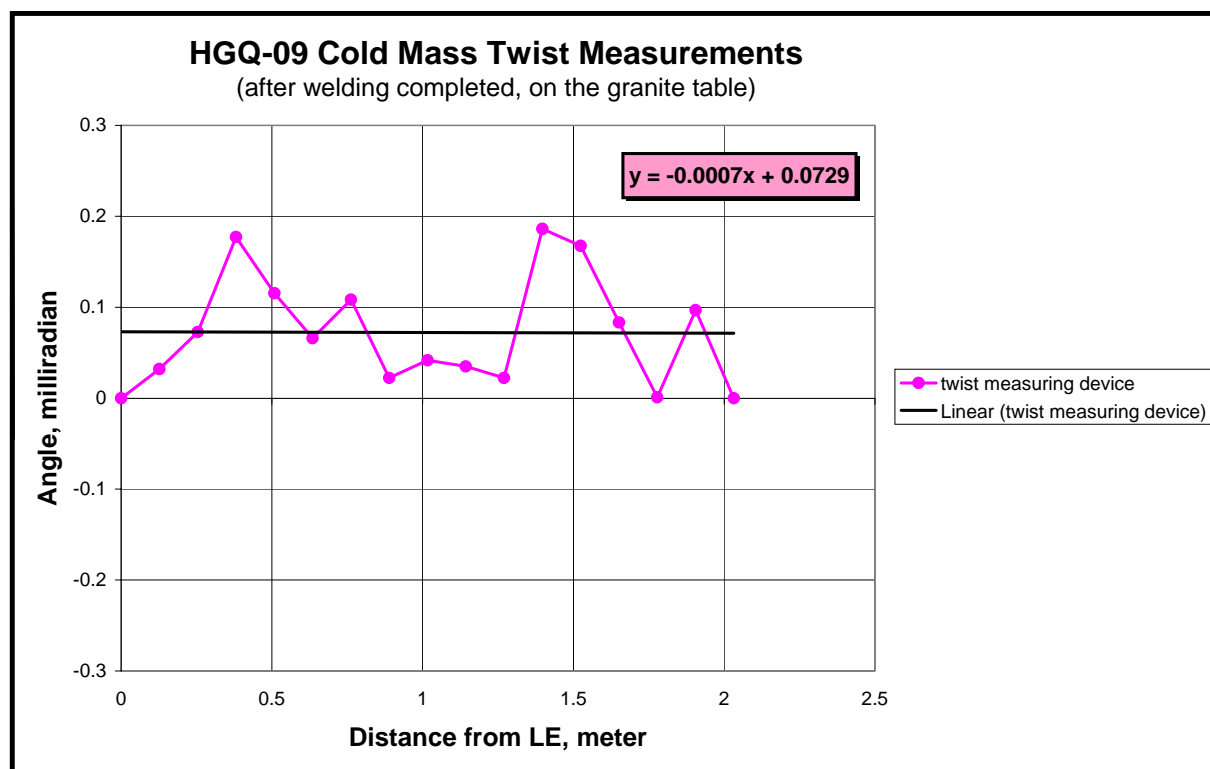
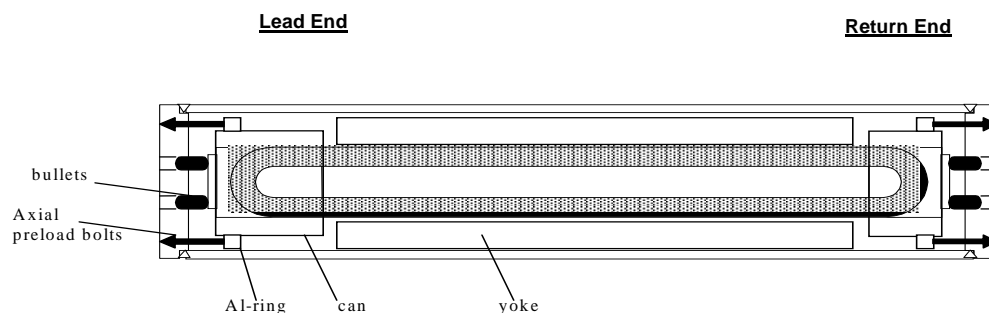


Fig 7.3.2: HGQ-09 Cold Mass Assembly Twist Measurements

## 7.4 Axial Loading (Bullets & Bolts):

The axial support system of the magnet is shown below:



**Fig 7.4.1: Axial Support of the Cold Mass Assembly**

The end load is applied by hand tightening the bullets to the bullet preload plate, then tightening the axial preload bolts to the specified amount. Strain gauges mounted onto the bullets provide feedback on the amount of force being applied. The gaps between coil end-saddles and the bullet preload plate was filled by “green putty”. The bullets for HGQ-09 bullets were instrumented but the bolts were not. Bullets were calibrated both warm and cold. The axial loading system used for HGQ06 and HGQ08 was used for HGQ-09. The bolts were torqued until the desired load was achieved on the bullets. The relationship between load and torque on the bolts was analytically calculated and verified by the previous bolts that were instrumented for HGQ-06.

Each bolt is torqued to 1200 inch-lbs. With that torque, the bolt applies 8,000-lbs. tension load to the magnet. As a result of the loading of the magnet with bolts, the bullets are subjected to a compressive load of 2,000 lbs. each. So the total force at each end of the magnet is 24,000-lbs. tension.

The loading phases and the final bullet loads are listed below:

	Q1	Q2	Q3	Q4
LE	2239	2188	2210	2358
RE	2127	1959	2027	2118

The loading scheme was as follow:

RE 100,200,300,400,500,600 inch-pound  
LE 100,200,300,400,500,600

RE 720,840,960,1080  
LE 720,840,960,1080

See the HGQ08 Fabrication Report (TD-99-071) , Figure 7.4.2, for a complete description of the relationship between bolt torque and bullet load in a “typical” magnet.

## **8.0 Final Assembly**

### **8.1 Quadrant Splices:**

**HGQ09 is the fourth magnet to be completed with double lead quadrant splices. All coils on HGQ09 have two leads per quadrant extending from the end, one being the usual coil lead and the other consisting of cable made with copper only strands, to be used as a stabilizer. All previous magnets had only single leads, except HGQ06, HGQ07 and HGQ08. Parts on the end that enclose the leads required some revisions to accept the double layers of cable. The new configuration of the double lead quadrant splices can be found in the assembly drawing MD-344925. The splice soldering tooling was also modified to accommodate four cables and the solder thickness.**

The double lead design has one complication. When the splice is made, it is necessary that the two coil leads be soldered directly to each other, with the stabilizer (copper only) leads on the outside, as shown in Figure 8.1.1. This occurs naturally in two of the three quadrants to be spliced. In one of the splices, however, as the leads extend out of the magnet and are placed together, the stabilizer from one of the coils is sandwiched between the two coil leads. This problem was solved by cutting the stabilizer just before the splice and reversing its position, as shown in Figure 8.1.2.



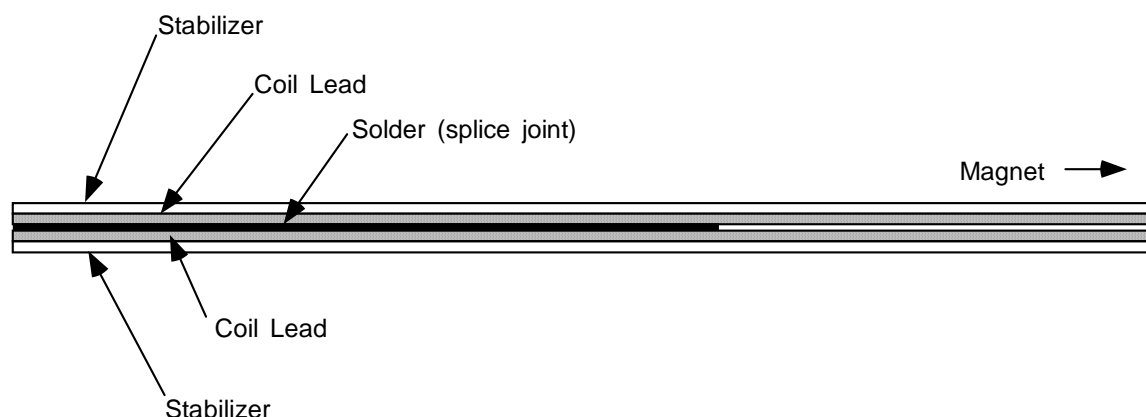


Fig 8.1.1

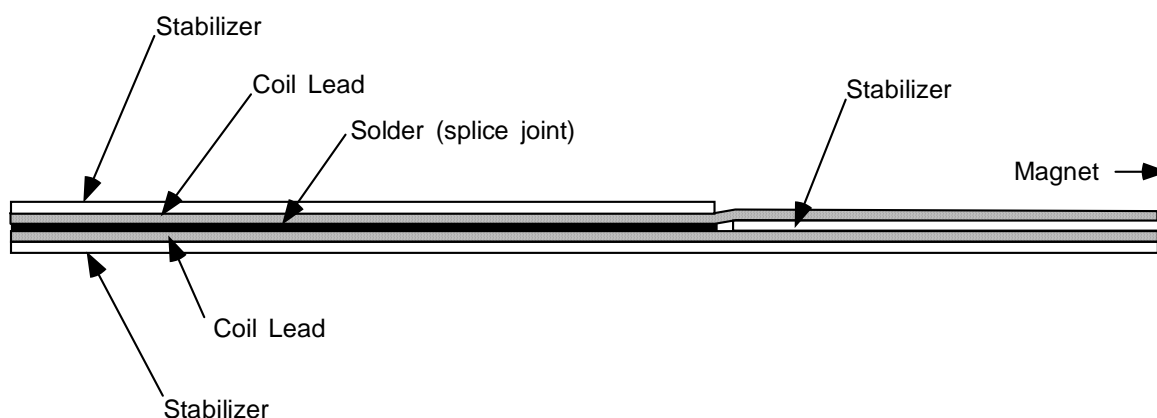


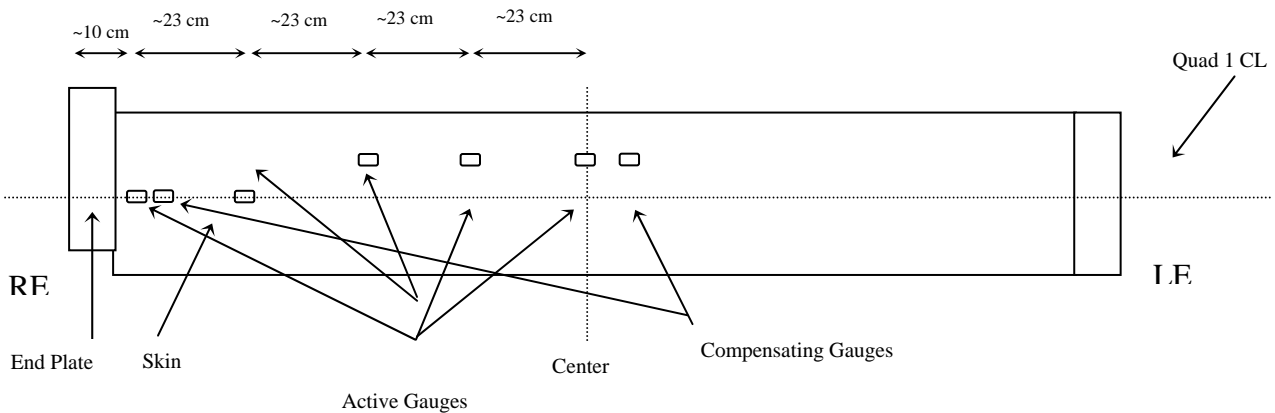
Fig 8.1.2

The first experiences with the double lead quadrant splices were with HGQ-06, HGQ-07 and HGQ-08. The same technique used for the previous magnets was repeated. The cable insulation during splicing was replaced to eliminate of a short during the bending of the cables for the splice. The quadrant splices were installed successfully to HGQ-09.

## 8.2 Skin Gauges: (From Joe Ozelis)

A total of 10 active strain gauges (Stk. # WK-09-250BG-350) were mounted in a longitudinal orientation along the length of the magnet. They were spaced approximately 23 cm apart, beginning about 10 cm from the end of the return end endplate, up to the cold mass center. Five were placed along the centerline of quadrant 1, and five were placed on a line 45 degrees from the centerline of quadrant 1, between quadrants 1 & 2. Compensating gauges were placed in a longitudinal orientation adjacent to the return end and centerline active gauges, co-linear with the active gauges.

In total, 14 strain gauges were placed on the shell, 10 active and 4 compensating. All were oriented so that their grids are parallel to the longitudinal axis of the cold mass. See the diagram below:



**Fig 8.2.1: Skin Gauge Layout (Side view of the skin)**

Sensor	VMTF name	Z-position	Sensor	VMTF name
HGQSk#105	: SkAcL010-1	10 cm	HGQSk#112	: SkAcL010-2
HGQSk#106	: SkAcL033-1	33 cm	HGQSk#113	: SkAcL033-2
HGQSk#107	: SkAcL056-1	56 cm	HGQSk#114	: SkAcL056-2
HGQSk#108	: SkAcL079-1	79 cm	HGQSk#115	: SkAcL079-2
HGQSk#109	: SkAcL104-1	104 cm	HGQSk#116	: SkAcL104-2
HGQSk#110	: SkCoL010-1	10 cm	HGQSk#117	: SkCoL010-2
HGQSk#111	: SkCoL104-1	104 cm	HGQSk#118	: SkCoL104-2

On Q1 centerline  
Q2

45 degrees from Q1 towards

Sensor #	Orientation	Type	z-position (cm from RE Endplate)	$\theta$ -position (degrees from Q1 centerline)	VMTF name
HGQSk#105	Longitudinal	Active	10	0	SkAcL010-1
HGQSk#106	Longitudinal	Active	33	0	SkAcL033-1
HGQSk#107	Longitudinal	Active	56	0	SkAcL056-1
HGQSk#108	Longitudinal	Active	79	0	SkAcL079-1
HGQSk#109	Longitudinal	Active	104	0	SkAcL104-1
HGQSk#110	Longitudinal	Comp	10	0	SkCoL010-1
HGQSk#111	Longitudinal	Comp	104	0	SkCoL104-1
HGQSk#112	Longitudinal	Active	10	45	SkAcL010-2
HGQSk#113	Longitudinal	Active	33	45	SkAcL033-2
HGQSk#114	Longitudinal	Active	56	45	SkAcL056-2
HGQSk#115	Longitudinal	Active	79	45	SkAcL079-2
HGQSk#116	Longitudinal	Active	104	45	SkAcL104-2
HGQSk#117	Longitudinal	Comp	10	45	SkCoL010-2
HGQSk#118	Longitudinal	Comp	104	45	SkCoL104-2

Table 8.2.1: HGQ-09 Shell Gauges

### 8.3 Final Electricals

HGQ-09 was hi-potted coil to ground, heater to ground and heater to coil at 1500 V. Leakage is required to be less than 0.5  $\mu$ A at 1500 V. All the coils and the outer strip heaters passed the hi-pot test.

The final electrical data collected before shipping to MTF:

	Resistance ohm	Ls M H	Q
<b>Q1 - inner</b>	.0853	181.68	2.25
<b>Q1 - outer</b>	.1075	317.23	2.29
<b>Q2 - inner</b>	.0848	181.10	2.25
<b>Q2 - outer</b>	.1069	311.12	2.32
<b>Q3 - inner</b>	.0848	181.58	2.18
<b>Q3 - outer</b>	.1081	313.96	2.27

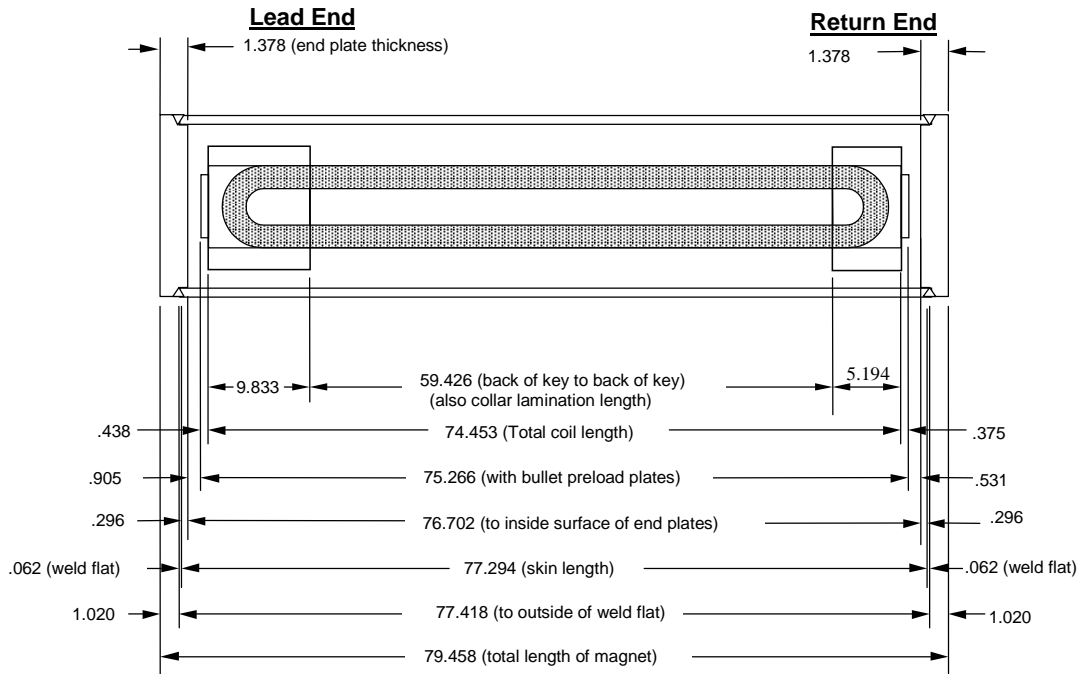
<b>Q4 - inner</b>	.0852	181.43	2.26
<b>Q4 - outer</b>	.1076	310.27	2.28
<b>Q1 – Quadrant total</b>	.1920	814.36	3.56
<b>Q2 – Quadrant total</b>	.1922	810.15	3.67
<b>Q3 – Quadrant total</b>	.1927	809.00	3.58
<b>Q4 – Quadrant total</b>	.1931	805.86	3.63
	<b>Resistance ohm</b>	<b>Ls MH</b>	<b>Q</b>
<b>Magnet Total</b>	0.7770	4.65	4.68

Table 8.3.1: Magnet Resistance, L and Q measurements.

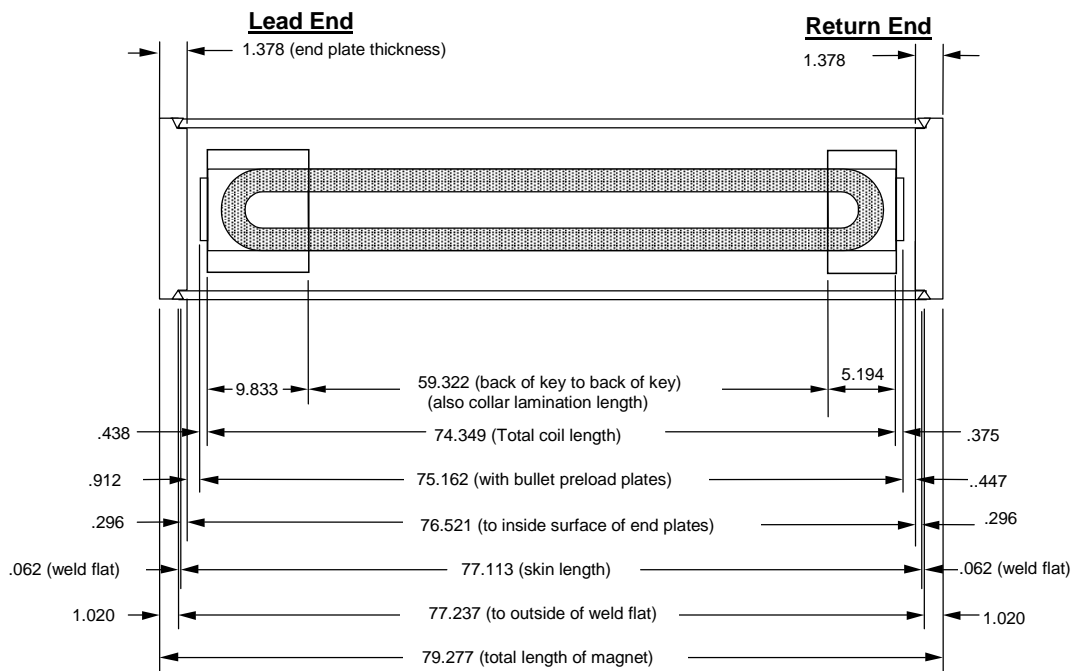
<b>Heater</b>	<b>Resistance ohm</b>
Q-1/2 – outer	3.768
Q-2/3 – outer	3.727
Q-3/4 – outer	3.837
Q-4/1 - outer	3.803

Table 8.3.2: Heater resistance measurements

## 8.4 Mechanical Measurements



**These are the design dimensions for HGQ09**



**These are the measured dimensions for HGQ09**

The total magnet length shown in the above figure is derived from the collared coil length measurements and the design size of components such as end plates, collets and preload plates. The total magnet length was measured independently after construction to be 79.375 inches long. The source of the .098 inch discrepancy is not understood.